

Efficiently Estimating Salmon Escapement Uncertainty Using Systematically Sampled Data

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ABSTRACT Fish escapement is generally monitored using nonreplicated systematic sampling designs (e.g., via visual counts from towers or hydroacoustic counts). These sampling designs support a variety of methods for estimating the variance of the total escapement. Unfortunately, all the methods give biased results, with the magnitude of the bias being determined by the underlying process patterns. Fish escapement commonly exhibits positive autocorrelation and nonlinear patterns, such as diurnal and seasonal patterns. For these patterns, poor choice of variance estimator can needlessly increase the uncertainty managers have to deal with in sustaining fish populations. We illustrate the effect of sampling design and variance estimator choice on variance estimates of total escapement for anadromous salmonids from systematic samples of fish passage. Using simulated tower counts of sockeye salmon *Oncorhynchus nerka* escapement on the Kvichak River, Alaska, five variance estimators for nonreplicated systematic samples were compared to determine the least biased. Using the least biased variance estimator, four confidence interval estimators were compared for expected coverage and mean interval width. Finally, five systematic sampling designs were compared to determine the design giving the smallest average variance estimate for total annual escapement. For nonreplicated systematic samples of fish escapement, all variance estimators were positively biased. Compared to the other estimators, the least biased estimator reduced bias by, on average, from 12% to 98%. All confidence intervals gave effectively identical results. Replicated systematic sampling designs consistently provided the smallest average estimated variance among those compared.

Annual escapement for anadromous salmonids is often estimated from nonreplicated systematic hourly counts (Seibel 1967), made either visually in clear rivers from elevated towers (tower counts; Cousens et al. 1982; Anderson 2000) or hydroacoustically in clear or turbid systems (see review by Ransom et al. 1998). These escapement estimates are critical in determining reproductive success of a given brood year and in developing sustainable fishery management plans (Cousens et al. 1982; Eggers et al. 1995; Fair et al. 2004). Equally critical to sound management are variance estimates of the annual escapement, ideally ones that have low bias and are efficient.

There are many variance estimators for nonreplicated systematic sampling, yet all are

biased (Yates 1948; Cochran 1977; Wolter 1985). The best estimator depends on the process being sampled; an estimator inappropriate for the specific process can give highly biased or inefficient estimates (Wolter 1985; Skalski et al. 1993). For example, the naïve variance estimator, which treats the observa-

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tions as a simple random sample, pools both process variation and sampling variation in its estimate. Simulation studies of processes exhibiting nonrandom patterns, such as stratification, autocorrelation, or linear trends, have shown this estimator can overestimate the true sampling variance by as much as 300% (Wolter 1985; Table 7.3.5; Skalski et al. 1993). The magnitude of the bias depends on the exact nature of the underlying process pattern, limiting general conclusions.

Fish passage generally exhibits regular patterns in time due to processes such as diurnal movement behaviors, tidal fluctuations, the impact

of commercial fisheries openings, or seasonal patterns in returns (Becker 1962). Stratification has been used in attempts to remove this process variation in nonreplicated systematic escapement counts. One approach poststratified observations by count magnitude at the end of the season then treated the sample as a stratified random sample to estimate sampling variance (Mathisen 1957; referenced in Becker 1962). This ignores uncertainty associated with estimating the population strata proportions and does not allow control of sampling effort to achieve a minimum sample size with-

in each stratum or optimally efficient estimates (Overton and Stehman 1996). Another approach stratified by time, e.g., four or six hour blocks, then treated the sample as a (systematically) stratified sample to estimate sampling variance (Table 1; Skalski et al. 1993).

Tower and hydroacoustic counts of fish escapement are expected to exhibit autocorrelation and nonlinear patterns. For such processes, a general review of variance estimators for nonreplicated systematic samples broadly recommended two estimators defined further below, termed V4 and V5, with the latter

Table 1.

Estimators for variance of total estimated escapement, $\hat{V}(\hat{Y})$, from a systematic sample of n observations, $\{y_j\}$, where j indexes observation sequence; f is the proportion of the possible observations that were actually collected ($f = 1/6$ for all simulations in this study).

Estimator	$\hat{V}(\bar{y})$	Assumed Design
Naïve ^a	$(1-f)(1/n) \sum_{j=1}^n (y_j - \bar{y})^2 / (n-1)$	Simple random sample
Stratified ^b	$\sum_{Strata i=1}^k N_i^2 (1-f_i) \frac{s_{Strata i}^2}{n_i}$, where $s_{Strata i} = \sqrt{\frac{1}{n_i-1} \sum_{j=1}^{n_i} (y_{i,j} - \bar{y}_{Strata i})^2}$	Stratified random sample
V2 ^c	$(1-f)(1/n) \sum_{j=2}^n a_j^2 / (2(n-1))$, where $a_j = y_j - y_{j-1}$	Non-replicated Systematic sample
V4 ^c	$(1-f)(1/n) \sum_{j=3}^n b_j^2 / (6(n-2))$, where $b_j = y_j - 2y_{j-1} + y_{j-2} = (y_j - y_{j-1}) - (y_{j-1} - y_{j-2})$	
V5 ^c	$(1-f)(1/n) \sum_{j=5}^n c_j^2 / (3.5(n-4))$, where $c_j = y_j / 2 - y_{j-1} + y_{j-2} - y_{j-3} + y_{j-4} / 2$	

Note: The estimated variance of the total escapement, $\hat{V}(\hat{Y})$, is the product of $\hat{V}(\bar{y})$ and the square of an expansion factor dictated by the sampling design (see Table 3).

^a Cochran (1977).

^b Suggested by Skalski et al (1993); n_i units sampled from N_i total units in strata i , $f_i = n_i / N_i$.

^c Wolter (1985).

Table 2.Total escapement 95% confidence interval estimators for a non-replicated systematic sample $\{y_i\}$ of n observations (from Skalski et al. 1989, 1993).

Interval	Formula	Assumptions
Normal	$\hat{Y} \pm 1.96\sqrt{\hat{V}(\hat{Y})}$	$\hat{Y} \sim \text{Normal}(Y, V(\hat{Y}))$
Lognormal	$\hat{Y} \times \exp\left(\pm 1.96\sqrt{\hat{V}(\hat{Y})/\hat{Y}^2}\right)$	$\log(\hat{Y}) \sim \text{Normal}(\log(Y), V(\hat{Y})/\hat{Y}^2)$
Lognormal ^a	$\hat{Y} \times \exp\left(\pm 1.96\sqrt{\hat{V}(\hat{Y})\left(\frac{1}{\hat{Y}^2} + \frac{3\hat{V}(\hat{Y})}{\hat{Y}^4}\right)}\right)$	$\log(\hat{Y}) \sim \text{Normal}(\log(Y), V(\hat{Y})\left(\frac{1}{\hat{Y}^2} + \frac{3V(\hat{Y})}{\hat{Y}^4}\right))$
Square Root ^b	$(\sqrt{\hat{Y}} \pm 1.96\sqrt{\hat{V}(\hat{Y})/4\hat{Y}})$	$\sqrt{\hat{Y}} \sim \text{Normal}(\sqrt{Y}, V(\hat{Y})/4Y)$

Note: Log-transformations suggested by right-skewed observations.^a Skalski et al. (1993).^b Skalski et al. (1989).

preferable for larger samples (Wolter 1984, 1985). The estimators use differences among consecutive observations to remove short-term autocorrelation and local trends. However, simulation studies specifically of fish passage over 2–3 d in dam bypasses comparing these and other estimators identified V4 and the time-stratified variance estimators as best, with comparable bias (Skalski et al. 1993). Thus, the best estimator for a given context depends on the underlying process and the number of observations.

Annual escapement is expected to be influenced by different processes than the short passage series investigated by Skalski et al. (1993). We therefore compared five variance estimators for total annual escapement estimates by simulating tower count samples using nonreplicated systematic sampling (Table 1). The study simulated nonreplicated systematic samples of tower counts of Kvichak River sockeye salmon escapement in Bristol Bay, Alaska (Anderson 2000). The five variance estimators were compared to find the least biased. Four confidence interval estimators were also compared in terms of expected coverage and mean interval width (Table 2).

Having identified the least biased variance estimator for nonreplicated systematic sampling of tower counts, we then compared five

systematic sampling designs to identify the one with the smallest expected variance estimate (Table 3).

While focused on counting tower observations, our study methods are applicable to any systematic sampling context. The specific conclusions depend on the nature of the underlying process, and hence directly apply only to systematic sampling of annual fish escapement in comparable systems, such as hydroacoustic monitoring of salmon escapement (e.g., Eggers et al. 1995; Burwen and Bosch 1996).

Methods

Simulation Study Data

Sampling was simulated on tower passage “censuses” created from Kvichak River tower count observations of sockeye salmon at Igiugig in 1983 and 2002 (Yuen and Nelson 1987; West 2003). These years represent the extremes of escapement and catch rates within a single river system and allow comparison of variance estimators and sampling schemes on both large and small escapements. The 1983 Kvichak run had an estimated harvest of 16.5 million fish and escapement of 3.57 million fish, with 79% exploitation rate (Yuen and Nelson

1987). The 2002 run had zero estimated harvest and escapement of 0.70 million fish (West 2003).

In 1983, hourly 10-min tower counts were collected each and every hour from 1700 hours on June 20 until the end of July 23. For the simulation study, a census of complete 10-min counts was generated using the observed counts from June 27 through July 23 (Figure 1a), the first week of observations being excluded as they were predominantly zero. In 2002, hourly 10-min tower counts were collected each and every hour from 0001 hours on June 21 until the end of July 18. For the simulation study, a census of complete 10-min counts was generated using the observed counts from June 27 through July 18 (Figure 1b), the first days of observations being excluded as they were predominantly zero.

Each census of complete 10-min counts was generated by linearly interpolating

between two consecutive observations then adding random error:

$$y_{time\ i+k/6}^{census} = \max \left(0, y_{time\ i}^{observed} + \left(y_{time\ i+1}^{observed} - y_{time\ i}^{observed} \right) \frac{k}{6} + \varepsilon \right) \quad (1)$$

where $k = 1, \dots, 6$ identified the 10-min period (potential sampling event) after observation i for which a count was being generated, and

$$\varepsilon \sim Uniform(-|y_{time\ i+1} - y_{time\ i}|, |y_{time\ i+1} - y_{time\ i}|) \quad (2)$$

Nonreplicated Systematic Samples

Each year's census data were used as the basis for simulating two nonreplicated systematic sampling designs: 10 min every h and 20 min every 2 h (Table 3). Standard protocol for towers in Alaska is to count 10 min at the top of every hour for the duration of the run (Anderson 2000). All six possible samples under each design were simulated.

A sample observation consisted of both a left bank and a right bank component, but all calculations were based on their sum:

$$y_{time_i} = right_count_{time_i} + left_count_{time_i} \quad (3)$$

Twenty-four-hour-a-day sampling was simulated.

Variance Estimators

Each variance estimator (Table 1) was

Table 3.

Systematic sampling designs investigated for estimating total sockeye salmon escapement from tower counts (see Becker 1962, Anderson 2000).

Design		Daily mean escapement, \bar{y}	Expansion ^a	Possible Samples ^b
Stratified Systematic ^c		$\sum_{Stratum=1}^k \bar{y}_i / 6N$	6 x 24 x N	10626 ^N
Non-replicated Systematic	20 m / 2 H	$\sum_{i=1}^n y_i / n$	6 x 24 x N	6
	10 m / 1 H	$\sum_{i=1}^n y_i / n$	6 x 24 x N	6
Replicated Systematic	4 @ 10 m / 4 H	$\sum_{j=1}^4 \left(\sum_{i=1}^n y_{ij} / n \right) / 4$	24 x 24 x N	10626
	2 @ 10 m / 2 H	$\sum_{j=1}^2 \left(\sum_{i=1}^n y_{ij} / n \right) / 2$	12 x 24 x N	66

Note: Total annual escapement is estimated by expanding the daily mean escapement: $\hat{Y} = (\text{Expansion}) \times \bar{y}$.

^a units/hr x hrs/day x days.

^b Number of possible samples given a sampling period of N consecutive days.

^c Simple random sample of four 10 m counts from each consecutive 4 hour period, proposed by Skalski et al. (1993). This design uses the sample mean escapement of each consecutive four hour observation strata.

applied to each season sample generated from each nonreplicated systematic sampling design (Table 3).

Let \hat{Y} denote the estimated total annual escapement and $\hat{V}_A(\hat{Y})$ its estimated sampling variance using estimator A (e.g., 'A' = naïve, V2, ...). That is, $\hat{V}_A(\hat{Y})$ is the square of the standard error for \hat{Y} . Let $\overline{\hat{V}_A(\hat{Y})}$ be the expected sampling variance, i.e., the mean, across all possible samples, of the sampling variance estimates $\hat{V}_A(\hat{Y})$. Finally, let $V_{true}(\hat{Y})$ be the true sampling variance (i.e., the actual variance of \hat{Y} across all possible samples). The bias of each variance estimator,

$$\text{Bias}(\hat{V}_A(\hat{Y})) = \overline{\hat{V}_A(\hat{Y})} - V_{true}(\hat{Y}) \quad (4)$$

was calculated from all possible samples under each design.

Confidence Interval Estimators

Four 95% confidence interval estimators were compared using the nonreplicated systematic samples (Table 2). Each interval estimator was calculated using each variance estimator for each simulated annual sample, but only the results from the least biased variance estimator are reported.

Interval estimators were compared in terms of their coverage and their mean width. Coverage was calculated as the percent of the possible samples, under a given sampling design, whose confidence interval estimates for total escapement actually contained the true total escapement. Ideal coverage was 95%. Interval estimator efficiency was assessed using the mean interval width, the difference between upper and lower bounds, across all possible samples for the sampling design.

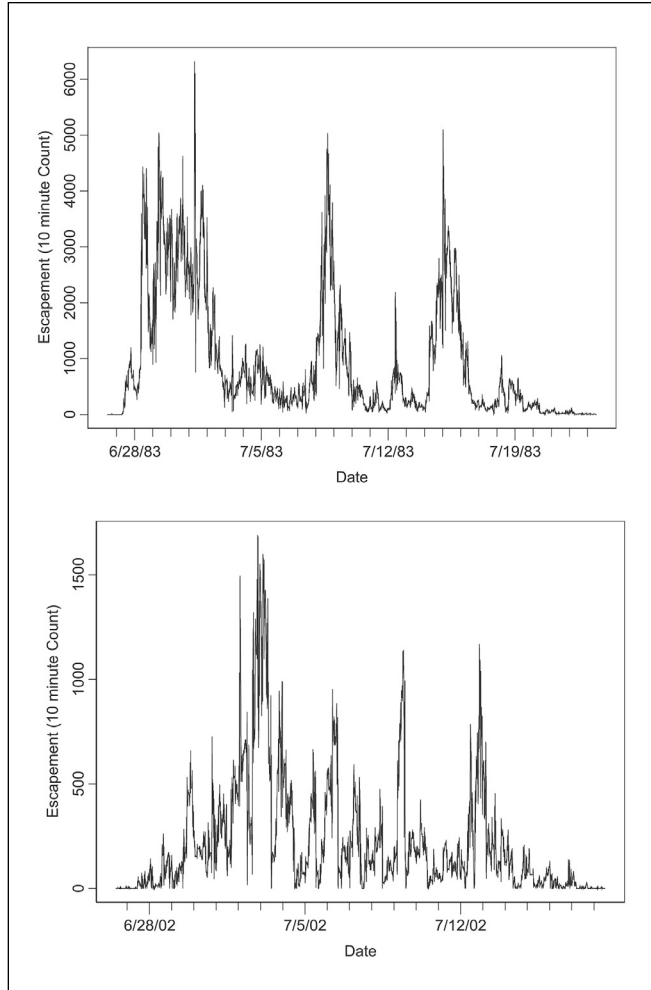


Figure 1. 'Census' of 10 min counts for Kvichak River sockeye salmon escapement – (a) 1983, (b) 2002, created from systematically sampled 10 m/H observations as described in text. Noon on each day is marked along the horizontal axis; note change in vertical scale.

Other Systematic Sampling Designs

Three other systematic sampling designs were investigated, each allowing for unbiased variance estimates: a stratified systematic sampling design and two replicated systematic sampling designs (Table 3). All designs maintained a sampling effort of 10 min per hour. In stratified systematic sampling, four 10-min periods were randomly selected in each consecutive 4-h period. The total annual escapement and its variance were estimated using

standard formulas for stratified random sampling (Table 1).

One replicated systematic sampling design randomly selected four 10-min periods in each consecutive 4-h period. These were the starting points of four independent systematic samples, each 10 min per 4 hours, and each providing an estimate of total annual escapement. The four estimates were averaged for the final estimated total annual escapement. The variance of the four estimates was calculated using the naïve estimator (Table 1) for an unbiased estimate of $\hat{V}_{\text{Replicated Sys.}}(\hat{Y})$. Similar procedures held for the other replicated systematic sampling design of two systematic samples of 10 min every 2 hours (Table 3).

Design Comparisons

Designs were compared for true sampling variance, $V_{\text{True}}(\hat{Y})$, their bias (equation 4), and the sample to sample variation of their variance estimates,

$$\text{Var}(\hat{V}_A(\hat{Y})) \quad (5)$$

For nonreplicated systematic sampling designs, the variance estimator identified in the first stage of the study as being least biased was used. Quantities were estimated from all possible samples (Table 3).

All simulations and calculations were conducted using S-Plus 6.2 (Insightful, Inc., Seattle, WA.) or the freeware R language and environment (<http://www.r-project.org/>). The variance and confidence interval estimators are available as R/S-Plus functions or Excel® (Microsoft, Inc, Redmond, WA.) macros from the first author.

Results

Variance Estimators for Nonreplicated Systematic Samples

All estimators were positively biased, with V5 the least biased for both high and low escapement years under both designs (Table 4). Compared to the other estimators, using V5 reduced the bias, on average, from 12% (V4) to 98% (naïve) (Table 4).

Confidence Interval Estimators

Even using the least biased variance estimator, V5, all interval estimators achieved 100% coverage versus the nominal 95% coverage for both high and low escapement years under both nonreplicated designs. Note that this variance estimator was positively biased and there were only six possible interval estimates for estimating coverage. While the interval endpoints differed, the mean interval width

for a given year was the same to three significant figures regardless of interval estimator, hence are not reported.

Systematic Sampling Designs

Designs greatly differed in their true sampling variation, with the nonreplicated designs performing best and stratified design worst (Table 5; Figure 2). The general pattern was fairly consistent across both high and low escapement years (Figure 2). Designs great-

Table 4.

Bias of non-replicated systematic sample variance estimators for total annual escapement, by data source year and sampling design.

	1983 Series (units 10 ⁸)		2002 Series (units 10 ⁷)		
	10 m / 1 H	20 m / 2 H	10 m / 1 H	20 m / 2 H	
$V(\hat{Y})$	3.4	0.4	9.1	7.9	
Estimator	Bias		Reduction by V5 ^a		
Naïve	233.6	1878.6	111.9	934.1	97.5%
Stratified	18.6	39.6	7.9	22.1	40.8
V2	12.6	39.6	5.9	31.1	37.8
V4	9.6	29.6	3.9	20.1	11.9
V5	9.6	24.6	2.9	19.1	

^a Mean reduction in bias relative to V5 = mean of (1 - bias / bias_{V5}).

Table 5.
Comparison of systematic sampling designs in terms of actual and expected sampling variance of the estimated total escapement and the sample to sample variation of the sampling variance estimate, by data source year.

Design	Units	1983			2002		
		$V(\hat{Y})$	$\bar{V}(\hat{Y})$	$Var(\hat{V}(\hat{Y}))$	$V(\hat{Y})$	$\bar{V}(\hat{Y})$	$Var(\hat{V}(\hat{Y}))$
		10^8	10^8	10^{16}	10^7	10^7	10^{14}
Stratified	4 @ 10 m / 1 H	20.2	19.1	7.6	15.6	15.4	5.3
Non-Replicated	20 m / 2 H	0.4	24.5	61.2	7.9	26.5	75.3
	10 m / 1 H	3.4	12.9	9.6	9.1	11.6	14.2
Replicated	4 @ 10 m / 4 H	9.8	9.8	51.7	8.6	8.6	41.8
	2 @ 10 m / 2 H	8.4	8.4	86.6	9.4	9.4	140.3

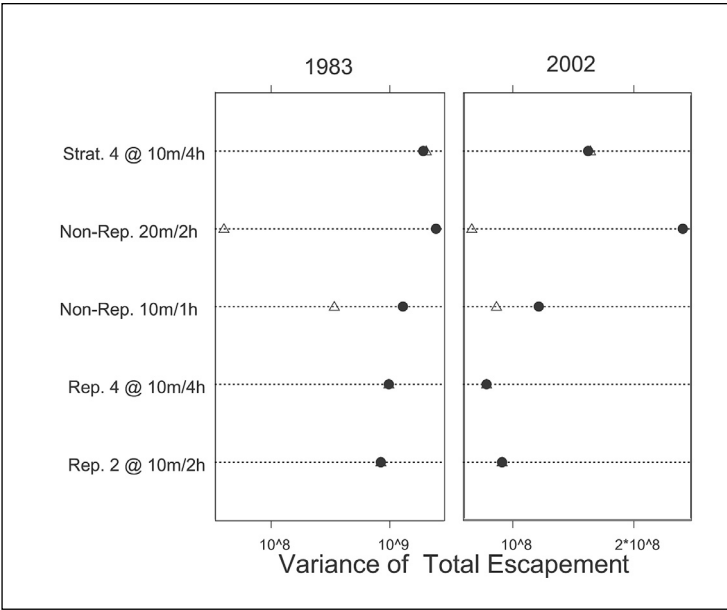


Figure 2. True variance (open triangles) and average estimated variance (solid circles) of the total escapement estimate under each of the investigated systematic sampling designs (row), by year (column). Columns differ in logarithmic horizontal scale (units fish²). The replicated systematic sampling designs provide unbiased estimates, hence the symbols overlap.

ly differed in their bias, with the replicated designs being unbiased and the nonreplicated designs being most biased (Figure 2). The general pattern of bias was consistent across both high and low escapement years (Figure 2). Designs differed in the sample to sample variation of their variance estimates, with the

stratified and nonreplicated designs varying the least (Table 5).

Discussion

Sound fisheries management requires accurate and precise estimates of both total escapement and its variance. This study showed the large reduction in uncertainty in total annual escapement of Pacific salmon possible through either careful selection of variance estimators, in the context of the most common sampling design, or careful consideration of alternative sampling designs.

Nonreplicated Systematic Sampling

The dominant sampling design for estimating escapement of Pacific salmon in Alaska is nonreplicated systematic sampling, a design with no unbiased variance estimator (Cochran 1977). For this design, the studies that do estimate variance generally employ either the naïve estimator, which ignores the process

variation that can dominate fish escapement, or V2, which only removes linear process trends (Wolter 1985).

This study reaffirmed the large bias of the naïve variance estimator for nonlinear, autocorrelated processes such as annual salmon escapement. However, the magnitude of the bias was noteworthy: fishery managers currently using the naïve estimator could reduce their uncertainty by 97% simply by switching to the V5 estimator (Table 4). Perhaps more importantly is the finding that even studies using the V2 estimator could reduce their uncertainty by an average of 38% by switching to V5 (Table 4). Given that calculations will be done on a computer, there seems little reason to purposely choose an estimator other than V5.

Estimators V4 and V5 were specifically developed to account for autocorrelation and nonlinear trends in systematic samples (Wolter 1984, 1985). The naïve estimator commingles this process variation into its estimate of sampling variation, thus overestimating the true sampling variation (Table 4). The V2 estimator removes only the linear component of this process variation. The stratified variance estimator implicitly assumes a constant escapement process within each 4-h period. If the sampled process exhibits regular patterns within this time scale and they appear in the systematic samples, then this estimator will commingle that process variation with the sampling variation.

When only a linear process trend occurs, estimators V4 and V5 remain effective. However estimator V2 has more associated degrees of freedom and hence is preferred at smaller samples (Wolter 1985).

For managers using nonreplicated systematic sampling for processes similar to seasonal salmon escapement, the V5 estimator is the clear choice for variance estimator (Table 1). The interval estimators were effectively identical in terms of both mean width and cover-

age, so we recommend the familiar normal interval (Table 2).

These recommendations differ somewhat from a similar study focused on hydroacoustic counts of fish passages in dam bypasses over two to three day periods on Columbia River (Skalski et al. 1993). That study concluded that V4 and stratified estimators were best, the difference in recommendations arising from the difference in underlying processes of interest and the differences in sample sizes available in each study—V4 being recommended over V5 for smaller sample sizes.

Other Systematic Sampling Designs

Of the five systematic designs investigated, the replicated systematic designs were the best overall, producing small, unbiased variance estimates (Table 5; Figure 2). The stratified design, while showing only slight bias, cannot be recommended as its true variance was at least 70% larger than any other design (Table 5). The nonreplicated designs, while exhibiting sample to sample variation on par with that of the replicated designs, cannot be recommended because of its bias (Table 5; Figure 2). Managers should consider whether the potential increase in precision and elimination of bias in variance estimation offered by replicated systematic designs warrants the slight increase in logistical effort.

While the replicated designs clearly outperformed the others, no strong recommendation can be made regarding which replicated design performed best (Table 5; Figure 2). The data sets themselves differed greatly in both process magnitude and sources of variation (e.g., harvest rates), thus the changing performance of the designs merely highlights the inherent tradeoff between number of replicates and frequency of sampling within a replicate. The improvement from choosing *either* of the replicated designs outweighed the impact of *which* design was chosen. Refinement as to which design could be investigat-

ed via a similar study using historic data for the process of interest.

Different processes exhibit different patterns and different systematic designs support variance estimators having different bias and precision. For processes similar to those investigated here, consider the recommendations given above; for other processes, apply the methods illustrated here to historic data or data from a similar study system. To simply rely on the most widely employed estimator is to risk needlessly magnifying the uncertainty associated with your systematic sample estimate.

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